AN EXPERIMENTAL DESIGN FOR MEASURING P, V, T, AND CONDUCTIVITY SIMULTANEOUSLY

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Abstract

We have designed an experiment in which it appears that we can measure the pressure, volume, temperature, and electrical conductivity of a metal simultaneously. These data aid in the modeling of conductivity and equation-of-state relations for metals that are driven to extreme states, for example in z-pinches, imploding liners, or high-power electrical fuses. Recent advances in the technique of measuring the temperature of a surface with variable spectral emissivity can produce measurement accuracy of a few percent. The experiment is arranged so the fuse material investigated is subject to one-dimensional movement only. In addition, conditions must be such that the state parameters are nearly uniform throughout the region being measured. In one such arrangement, a thin planar foil is sandwiched between two pieces of lithium fluoride and a suitably large current is passed through the foil. The initial heating is not one-dimensional due to the time required for the magnetic field to diffuse into the foil; however, for certain geometries of the foil (such as 3 cm wide and 0.008 cm thick), the conditions at the center of the foil satisfy the conditions of one-dimensionality after a few microseconds. The displacement of the foil interface with the lithium fluoride allows the computation of the density of the foil material (typically copper or aluminum). The velocity of the surface together with the known equation of state of the lithium fluoride gives the pressure at the interface and, by the one-dimensionality of the conditions, the pressure through the center of the foil. The conductivity is measured by measuring the electric field using voltage probes, with the current density inferred from a local measurement of the magnetic field at the surface of the foil. Other fuse geometries such as rods or cylindrical foils are also candidates for the experiment. Detailed two-dimensional calculations of the current and material flow have been performed and will be discussed.

I. INTRODUCTION

There are many high-current pulsed power experiments whose results depend critically upon the response of the materials to Joule heating and pressure. Examples include solid liner implosions [1], wire z-pinches [2], explosively formed fuses (EFFs) [3], electrically exploded fuses (EEFs) [4], magnetic flux compression generators (FCGs) [5], [6] and isentropic compression experiments (ICE) [7], [8]. In all of these examples, electrical conductors start out at ambient temperatures and pressures that are quite modest (often near ambient conditions). However, as they are subjected to transient high-current pulses, they undergo rapid heating. The resulting increase in internal energy typically reduces the material electrical conductivity in the solid state, and if there is expansion, further reduces conductivity. These processes continue through melt, vaporization, or even transition to ionized plasma phase if the heating is intense enough. If the material becomes highly ionized, the conductivity begins to rise again with increasing temperature according to the usual Braginskii [9] or Spitzer [10] scaling.

Electrically exploded fuses, used as high-power switching elements in inductive storage circuits, are designed to turn into a highly resistive vapor-like state very rapidly when the action (i.e., the time integral of the square of the current density) reaches a particular value. Here, one deliberately tries to prevent significant ionization to keep the conductivity as low as possible for as long as possible in order to interrupt current at the highest possible rate. Explosively formed fuses are used as switches and as voltage-forming elements in inductive storage circuits. They are explosively deformed as well as heated electrically. Other examples of devices where material is driven to extreme states are imploding liners and Z-pinches. Finally, FCGs use conductors that are driven explosively to compress their associated magnetic fields, thus amplifying current in a load. The exact trajectory through thermodynamic state space varies

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14. ABSTRACT

We have designed an experiment in which it appears that we can measure the pressure, volume, temperature, and electrical conductivity of a metal simultaneously. These data aid in the modeling of conductivity and equation-of-state relations for metals that are driven to extreme states, for example in z-pinches, imploding liners, or high-power electrical fuses. Recent advances in the technique of measuring the temperature of a surface with variable spectral emissivity can produce measurement accuracy of a few percent. The experiment is arranged so the fuse material investigated is subject to one-dimensional movement only. In addition, conditions must be such that the state parameters are nearly uniform throughout the region being measured. In one such arrangement, a thin planar foil is sandwiched between two pieces of lithium fluoride and a suitably large current is passed through the foil. The initial heating is not onedimensional due to the time required for the magnetic field to diffuse into the foil; however, for certain geometries of the foil (such as 3 cm wide and 0.008 cm thick), the conditions at the center of the foil satisfy the conditions of one-dimensionality after a few microseconds. The displacement of the foil interface with the lithium fluoride allows the computation of the density of the foil material (typically copper or aluminum).

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greatly for all these applications, and the conductivity varies depending on the exact thermodynamic state.

The ability to simulate an experiment or a device accurately can greatly reduce the number of iterations required to reach a given goal. The magneto hydrodynamic (MHD) codes needed to simulate the experiments listed above (such as CALE [11], MACH [12], and ALLEGRA [13] require equation of state (EOS) and conductivity models. Some recent papers in the literature have underscored the need for better material characterizations in order to reproduce experimental results with MHD codes [14].

In all of the above cases, the electrical conductivity may be the most important parameter. While the electrical conductivity of most materials is well characterized as a function of temperature at atmospheric pressure, there is a dearth of information regarding conductivity under different pressure and density conditions. There are the widely used SESAME tables [15], but they are generally considered a very gross approximation at best. For electrical conductivity, many researchers use a model described in a paper by Lee and More [16].

A paper by DeSilva [17] described an electrically exploded wire experiment where they attempted to simultaneously determine the electrical conductivity and thermodynamic state. The results of these experiments, using aluminum and copper, were used by Desjarlais [18] to modify the Lee-More model to more closely match experimental results. There has been some success with this approach, but more data is needed to further expand the knowledge base. One of the drawbacks of the DeSilva experiments was that they only measured the expansion of the material and relied on existing EOS data to infer the complete thermodynamic state.

In the experiment described here, we attempt to simultaneously determine the density, pressure, and temperature independently, while determining the electrical conductivity. Furthermore, by varying the pulsed power driver and tamping material, we should be able to vary the trajectory through state space. It is hoped that by this technique we will be able to greatly improve the knowledge of material electrical conductivities and thereby enable higher fidelity MHD simulations of a wide range of high-current pulsed power applications.

II. EXPERIMENTAL ARRANGEMENT

The experiment is set up so the expansion of fuse material is one-dimensional and can be performed in planar or axially symmetric geometry. We decided to do the initial experiments in the planar geometry, and this geometry will be the discussed below.

The expansion of the fuse material is impeded by a tamper in order to increase the pressure in the fuse material and to prevent a free expansion. There are several conditions that need to be satisfied by the fuse material and the tamper. As noted above, the expansion must be one-dimensional. By this we mean that the state

variables and the conductivity must vary by an acceptably small amount over the thickness of the fuse material. We consider a few percent a reasonable variation. The density, pressure, and temperature are measured at the surface of the fuse material and it is an assumption in the analysis of the data that there is no variation throughout the fuse material. The uniformity is a function of the material thickness and the rate with which the current density and the magnetic field penetrates the fuse material. We have found that for the equation of state, the conductivity model, and for the rate of change of the current we used that a foil thickness of 0.008 cm is acceptable. If the foil is substantially thicker, the state variables at the edge of the foil will be significantly different from the same variables in the interior of the foil. If the foil is substantially thinner, the error in measuring the density and pressure from the displacement and velocity of the foil / tamper interface becomes too large. The requirement of one-dimensionality extends to the tamper; the flow in the tamper need not be one-dimensional throughout the whole volume of the tamper, only in the region where the state variables are measured. That location is in the center of the foil for our geometry. Another condition which is imposed on the experiment is that the foil expansion is symmetric. We are only measuring the foil temperature and surface movement on one side of the foil; we are using the symmetry of the experiment to infer the conditions on the other side of the foil and that the foil center does not move.

III. FLOW IN THE FOIL GEOMETRY

One disadvantage of using a foil geometry is that the current in the foil is not uniform over the width of the foil as the current is ramped up. Initially, most of the current is concentrated at the edges of the foil, and it takes a while for the middle of the foil to heat uniformly. Nevertheless, our simulations of the hydro flow in the foil and tamper indicate that the configuration does arrive at a state which is suitably one-dimensional in a timely fashion.

The configuration used for most of the design calculation consists of a 0.008 cm thick foil, 3.0 cm wide, surrounded by lithium fluoride (LiF) crystal on both sides. The LiF crystal covers the width of the foil and is 1.0 cm thick on both sides of the foil. A return conductor helps manage the magnetic field and current variation over the width of the foil and surrounds the LiF crystals. We are using LiF crystals as the tamper because it provides optical access to the surface of the foil and thus permits the radiation from the hot foil to reach the spectrometer. In addition, LiF has been accurately characterized [19] in terms of its acoustic properties and refractive index at high pressures, and therefore allows measurement of the foil pressure. The pressure, volume, and temperature are measured at the center of the foil. The electric and magnetic fields required to calculate the resistivity may be measured either on the foil centerline or slightly off the
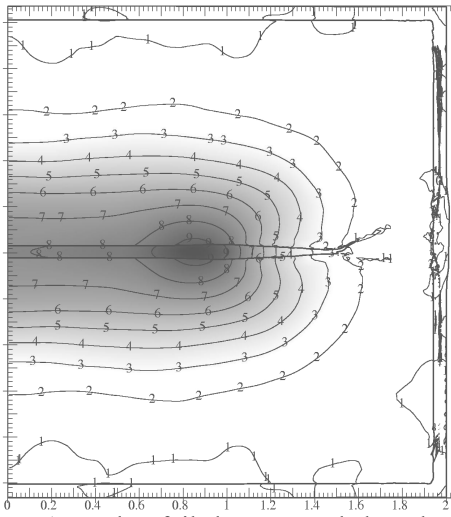
Figure 1. The foil has expanded and created a distribution of pressure in the LiF. At this time the expansion in the center of the foil is one-dimensional. The numbered lines are isobars.

centerline. Our calculations show that the electric field is near-constant in the direction perpendicular to the foil.

As the current is ramped up, the current density becomes very high at the edges of the foil. The consequent heating and expansion of the foil causes pressure waves to propagate into the foil and into the LiF crystal. The field and current are penetrating the foil material at the same time and causing it to heat up, though not nearly as hot as the foil at the edges. The pressure waves from the edges can cause inaccuracy in the calculation of the pressure in the center of the foil, but fortunately the expansion of the wave causes these pressure perturbations to be relatively insignificant. Fig. 1 shows the one-dimensional expansion calculated by CALE near the center of the foil as well as the distribution of pressure in the foil and the crystal. It is during this part of the foil expansion that the data will be acquired. The foil expansion will continue to be one-dimensional until the pressure waves from the foil edges meet in the center of the foil.

IV. TEMPERATURE MEASUREMENT

A non-invasive method of measuring the temperature of a surface has been developed at LLNL [20]. The method combines reflectivity and emissivity measurements over a range of wavelengths to enable the computation of the temperature of the surface as well as the spectral emissivity of the surface. The method is much more accurate than any other method known to the authors; measurements of the temperature of a pulse heated foil are accurate to approximately one percent, possibly better. The strength and uniqueness of this method of measurement is that it does not required previous knowledge of the emissivity of the surface. A lack of knowledge of the emissivity and its variation with wavelength is often the cause of temperature measurement errors on the order of tens of percent. The method uses sequential measurements of the emitted and the sum of the emitted and reflected light. The reflected light comes from an external source of full spectrum light. The duration of the measurements depends on the amount of light available and its frequency. For infra-red emission, with slow detectors and a scarcity of light, the signals can be acquired in a few tenths of a microsecond. In the present application, with the spectrum in the visible and ultra-violet ranges of wavelengths, the instrumentation is much faster and the measurement time is less. We expect to be able to measure the temperature from 2,000 degrees Kelvin to 20,000 degrees Kelvin.

V. PRESSURE MEASUREMENT

The measurement of pressure uses the wave relations and the published equation of state of the LiF [21]. We use a VISAR to measure the velocity of the interface between the LiF and the foil and thus obtain the material velocity $u(t)$ in the LiF. Using Lagrangian wave analysis [22] and the known wave velocity $C_L(u)$ in the LiF we can obtain the pressure at the interface. The differential form of the momentum conservation equation is then used to calculate the change in pressure dP for each step of the particle velocity du. ρ_0 is the initial density at zero pressure. The pressure is the integral of the relation

$$dP = \rho_0 C_L(u)du.$$

The pressure obtained from the velocity of the interface between the LiF and the foil can be compared with the pressure obtained from the hydro-dynamic calculations. This comparison is an indication of the accuracy we can expect in the experiment and also indicates the range in time and conditions for which we can expect the above equation to yield an accurate measurement of the pressure in the foil. The comparison shows that the relation is not accurate early in the calculation, before the foil melts. Once the foil melts, the accuracy is quite good until later in time. The deviation between the two calculations at that time is ascribed to a lack of one-dimensionality caused by the flow being driven toward the center from the edges of the foil. The Visar data should indicate when the foil melts, and optical imaging as well as experimental time should tell us when the edge effects have converged at the center.

VI. DENSITY MEASUREMENT

The density is inversely related to the foil thickness in one- dimensional planar flow. The data obtained during the experiment is the velocity of the foil surface. Integrating the velocity (and its error) gives the displacement (and its error). It is the error in the density

measurement that sets the lower limit on the foil thickness that can be used in the experiment.

VII. VOLTAGE AND CURRENT MEASUREMENT

We have considered several arrangements of voltage probes and B-dot loops to measure the value of the electric and magnetic fields necessary to calculate the resistivity of the foil. One of the arrangements [23] uses multiple loops to allow calculation of the surface magnetic field as well as the electric field in the foil. These arrangements require that wires are run near to and parallel to the surface of the foil. Normally, we would want to measure the voltages and the electric field on the centerline of the fuse. However, we can not locate wires near the fuse centerline because they would affect the response of the tamper to the movement of the fuse. Fortunately, it turns out that according to the MHD simulations the electric field is quite uniform in the direction normal to the foil centerline, even though the current density and conductivity, separately, are not. We can therefore place the electric field probe a small distance from the foil centerline.

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